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13. ABSTRACT *(Maximum 200 Words)*
Currently, a large suite of electronic systems used in commercial and industrial applications (which include, but are not limited to, automotive, nuclear power, and well logging systems) require cycle-life performance that would benefit significantly from components designed and optimized for higher temperatures (200C to 600C) under harsh environmental conditions.
This paper presents the development, characteristics and life tests of a >1kV, >300C reconstituted mica paper power electronics capacitor system, including a full-size 2.4 microfarad unit.
It should be noted that reconstituted mica paper capacitors are used in a variety of applications, and that they are particularly well suited for use in high voltage, high temperature electronic systems: silicone impregnated mica paper capacitors are available for operation at 260 C.

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Development and Characterization of a >1 kV Power Electronic Capacitor for >300°C Operation

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ABSTRACT

An electronic power capacitor system capable of operating at >300°C was developed that is based on commercial mica paper-aluminum foil in pressurized N_2. Single windings were used to develop an effective processing and conditioning procedure. Evaluation was based on life tests at 325-335°C with applied dc voltage stress. A full-size, 2.4 µF unit, consisting of a stack of 7 windings was life tested at with 2.0 kV_{dc} applied.

INTRODUCTION

The objective of this project was to develop a several µF, 1-2 kV power electronics capacitor using currently available materials and commercial capacitor manufacture processes. For this application, size, ≥0.02 J/cm^3 dielectric energy density (electrodes and containment reduce this by ~20 %), and shock resistance are important.

The operational temperature requirement of >300°C limited the dielectric to an inorganic or ceramic material, and the impregnant to a relatively inert gas such as air, N_2 and CO_2 (SF_6 is reactive above 250°C). The advantages of high electric strength organic polymer dielectrics and fluid impregnants could not be exploited here as these materials invariably decompose at 300°C. Some consideration was given to the recently developed borosilicate-evaporated electrode system, which could operate at >100 V/µm[1], but it entailed special design for shock resistance. The most promising dielectric material appeared to be reconstituted mica paper. This was realized from a search for commercially available high- temperature, kV and µF rated power electronic capacitors.

The Custom Electronics silicone impregnated reconstituted mica paper capacitor came closest to satisfy the thermal stress requirement with its maximum temperature rating of 260°C. This temperature limitation is due to the thermal degradation of the silicone polymer impregnant above 260°C. This capacitor provided a benchmark for size in the course of the high temperature development, its energy density being 0.02 J/cm^3, as its $\varepsilon_r = 5$, and operating voltage stress is 31.5 V/µm.

Reconstituted mica paper consists of small, thin and overlapping platelets of muscovite mica, and has sufficient strength to be self-supporting and to be wound into roll form for commercial use[2,3]; it is available in the thickness range of 12.7 μm (0.5 mil) to 50.8 μm (2 mil). The technology and properties of reconstituted mica paper polymer (epoxy, polyester and silicone) impregnated capacitors, and of the mica paper itself can be found in references 4-7.

While the mica paper was expected to be thermally stable well above 300°C, its development for this elevated temperature operation dealt with issues of: (1) a large capacitor dielectric area sustaining a sufficiently high voltage stress in a pressurized gas, and (2) satisfactory dielectric properties, i.e., high RC (low dc leakage current) and low dissipation factor. In a preliminary test, a small area sample of 25 μm mica paper (6 cm x 6.5 cm) in 30 psig CO_2 sustained 2 kV_{dc}, i.e., 80 V/μm.

Achieving the objective of this development, a high temperature power electronic capacitor, should benefit both present and new electric power systems by permitting the capacitor to be located close to the energy source that may be in or generate a hot environment, thereby minimizing series inductance, and also diminishing or eliminating altogether cooling energy and equipment. The applications include aircraft, automotive, nuclear power, and deep well logging systems electric/electronic power systems. The advantages of increased payload and efficiency, and decreased cost are obvious.

TEST CAPACITORS

The essential feature of this capacitor development effort was to ascertain effective processing, conditioning, gas "impregnant" and voltage stress capability of the 0.3 μF mica paper-aluminum foil winding elements that are used in the aforementioned full-scale 2 kV Custom Electronics silicone impregnated mica paper capacitors. The development and tests were done at Northrop Grumman. Experience has shown that this size test unit is sufficient to account for the high area effects of full-scale capacitors on efficiency of processing and conditioning, electric strength and dielectric properties.

Figure 1 is a picture of the windings prepared at Custom Electronics; their composition and dimensions are as follows.

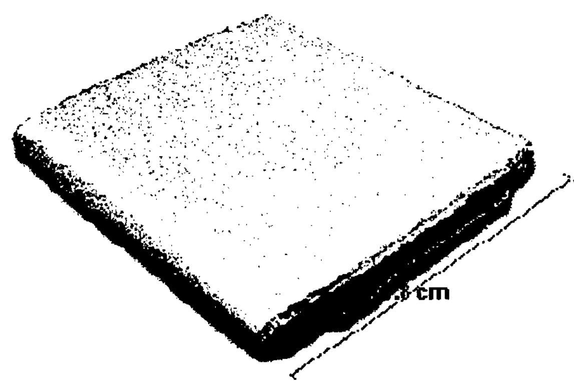

Figure 1. A 0.3 μF mica paper-Al foil winding with Cu spray applied to the foil edges.

- Two 23 μm (0.9 mil) + 1- 18 μm (0.7 mil) layers of mica paper + 6 μm (0.24 mil) Al electrode.
- 7.8 cm between edges at foil extensions x 6.6 cm x 0.57 cm at 2,300 lbs compression.
    - This compression gave the capacitor a dielectric thickness of 45 μm, with a measured capacitance of 0.3 μF, and a **dielectric constant of 3.4.**
    - That dielectric constant, which was measured, corresponds to 30 % voids in series with solid mica whose $\varepsilon_r = 7$.

The foil edges of the windings were coated with copper spray for lead connection to the electrodes. Initially, 0.075 mm, 1/4 inch nickel strip leads were attached with Aremco 497A (Ag-silicate) sealant; subsequently the nickel strips were wedged between two layers of the copper spray.

Test Capacitor Assembly, Processing and Conditioning

These 0.3 μF windings were processed (essentially dried), conditioned and life tested in an autoclave specially modified with two high voltage feed-throughs providing access for high voltage input and current monitoring. Dielectric properties were also measured under the controlled conditions in the autoclave after conditioning.

Each face of a winding was overlaid with 10 layers of 23 μm mica paper, one layer of 25 mil alumina and a 1/8 inch stainless steel plate; this mica paper and alumina provided major high voltage insulation to assure isolation of the active capacitor. This assembly was compressed to 2,300 lbs (based on Custom Electronics practice), and the plates were bolted together to maintain the compression, Figure 2.

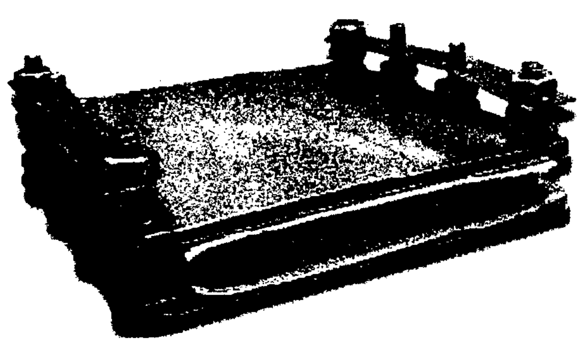

Figure 2. A 0.3 μF mica paper-Al foil winding mounted in a high temperature test fixture.

The following processing and conditioning steps were used to prepare the capacitor windings for life testing.

- Heat in air for >12 hours at 100-110°C; evacuate for >1/2 hour.
- Heat in 15-30 psig CO_2 or N_2 at ~250°C, ~320°C and at ~350°C for 2-3 hours + 15 minutes evacuation at each temperature.
    - It was found that the electric strength of a winding was lower before it was heated at ~350°C than subsequently. This precludes application of voltage during this processing step.
- **Conditioning.** The temperature was then decreased to ~320°C, the gas pressure was increased to 50 psig, and 2 kV_{dc} was applied. The leakage current generally decreased to <50μA (RC >12 s) in ~12 hours. This step is essentially the beginning of the life test. It may also be considered as a "burn-in" procedure.

LIFE TESTS AND DIELECTRIC PROPERTIES

The essential life test procedure was the application of dc voltage to a capacitor winding in the autoclave at ~320°C, with CO_2 or N_2 at a specified pressure. Leakage current was continuously monitored providing the RC, which usually increased with aging time. Failure occurred precipitously, apparently without forewarning such as increase in leakage current; it was, typically, a local dielectric puncture. Most of these punctures were ~1/2 inch from a foil edge, a few were at the foil edge, and some occurred where the winding was bent in the flattening process.

Capacitance and dissipation factor were measured at 1 kHz at the various temperature

levels during processing and during the life tests.

Life Tests in CO_2

Initial, and most life tests were made with pressurized CO_2 "impregnant" because the partial discharge inception and inception and extinction voltages of mica with a CO_2 ambient were found to be twice those with N_2[8]. However, as the work progressed the mica paper-Al foil dielectric was found to be more stable at the elevated test temperatures and voltages with an inert gas "impregnant", indeed N_2, than with CO_2. Nevertheless, the CO_2 life test data, Table 1, are valuable that they indicate voltage stress and possible gas pressure trends. (A ditto, ", in the Cap # column indicates continued testing of the same sample, but at a different applied voltage or gas pressure.)

Cap. #	Temp., °C	Appl. V, V_{dc}	CO_2 Press., psig	RC, s	Life, hrs
2	320-326	3,000	50	4	3
3	~325	3,000	50	3	8 min
4	320-329	2,500	5.5*	25	>113
"	329	2,750	5.5		0.5 min
5	330	2,500	5	3	1.25
7	327-330	2,500	4	7	3 min
9	330	2,500	50		0.5 min
6	330	2,500	50	47	>43
"	324	2,500	4	64	>66
"	328	2,500	5, $N_2/1\%H_2$	34	5 min
8	315-327	2,000	50	26	170
10	320-330	2,000	50	83	40
11	320-325	2,000	50	24	>91
"	319-325	2,000	2	20	140

* initially at 50 psig

Table 1. Life tests of ten 0.3 μF mica paper-Al foil windings in CO_2.

Extrapolating life as a function of voltage stress and temperature indicates that that this dielectric should sustain slightly less than 2,000 V_{dc}, perhaps 1,800 V_{dc} (40 V/μm), for hundreds of hours at ~300°C in a CO_2 ambient. Applied voltage levels of >2,500 V_{dc} (>62.5 V/μm) apparently give this dielectric a very short life at ~325°C.

Table 1 data indicate it may well be that after the capacitor is properly conditioned at an elevated gas pressure it may operate stably at near atmospheric pressure. The relatively long lives of Caps. 4 (before it was tested at 2,750 V_{dc}), 6 and 11 at rather low CO_2 pressures, between 2 and 5.5 psig, is noteworthy. Perhaps this was associated with preconditioning at 50 psig, their pressure during initial aging. In this connection it should be noted that the lives of Caps. 5 and 7 were very short, where the initial CO_2 pressures were 5 psig and 4 psig.

The rapid failure of Cap. 6 that followed when the CO_2 ambient gas was replaced with $N_2/1\%H_2$, might indicate that the mica paper dielectric is unstable in a reducing gas at the elevated temperature and relatively high voltage stress.

Life Tests in N_2: a Winding and a Capacitor Stack

First a mica paper-Al foil winding test capacitor was life tested in N_2, and because its life data showed significantly greater stability than with CO_2, a full-size, 2.4 μF capacitor, consisting of a stack of seven such windings, Figure 3, was likewise tested. Both units were processed, conditioned and aged in N_2 similarly to most of the test capacitor windings in CO_2. Table 2 presents the essential features of this aging data.

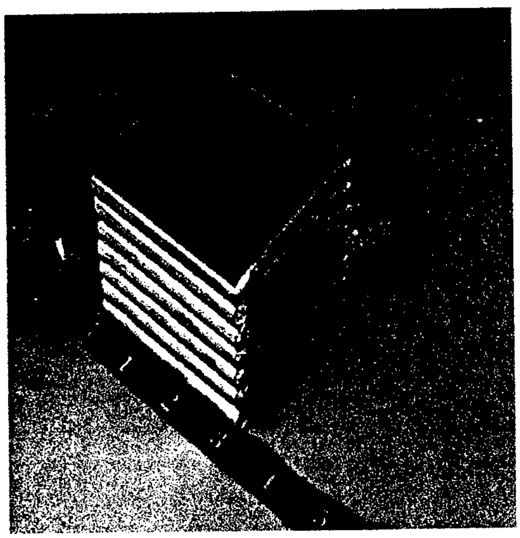

Figure 3. The full scale 2.4 μF capacitor stack of seven mica paper-Al foil windings.

Cap. #	Temp., °C	Appl. V, V_{dc}	N_2 Press., psig	RC, s	Life, hrs
12	325-330	2,000	50	22	>112
’’	341-348	2,000	50	13	>300
’’	348	<2,000	7		failed
13, 7-layer	325-335	2,000	50	145	~100

Table 2. Life tests of one 0.3 μF mica paper-Al foil winding, and one seven layer stack in N_2.

During the aging of the test capacitor winding a ripple current of 3 A_{rms} at 30 kHz was concurrently added to the dc voltage. Measurements with and without this ripple current showed that it had no effect on the RC or dissipation factor.

The following are some of the salient features of life test data obtained with pressurized N_2 compared with CO_2.

- It is evident that the mica paper dielectric is more stable with concurrently applied thermal and voltage stresses in pressurized N_2 than CO_2.
- The N_2 pressurized dielectric, unlike those pressurized with CO_2, did not sustain voltage stress at a reduced pressure after conditioning at a high pressure. However, the test in N_2 was at 348°C, while those with CO_2 were at lower temperatures, 320-330°C.
- The shorter life of the full-size capacitor than the single winding test capacitor is evidently due to its larger area effect in reducing long-term electric strength. It is noteworthy that its ~100-hour life is in the same range as the CO_2 pressurized test capacitor windings aged under the same conditions, Table 1.

Dielectric Properties

Capacitance and dielectric constant

The temperature coefficient of the test capacitor windings in CO_2 over the temperature range of 25°C to 350°C was found to be **44 ppm/°C**. Capacitance did not change with aging under the applied voltage and thermal stresses.

The relative dielectric constant of the winding is **3.4**.

Dissipation factor

Table 3 gives the dissipation factors of the 0.3 μF test capacitor windings in CO_2 over the temperature range of 25°C to 350°C before the onset of aging with applied voltage.

Temp., °C	DF @ 1 kHz
25	~0.0007
100	<0.002
250	~0.01
300	~0.015
325	~0.02
350	~0.03

Table 3. Dissipation factors of 0.3 μF mica paper-Al foil capacitor windings.

The dissipation factor, however, did increase during the aging tests with CO_2. Specifically, the dissipation factor of Cap.11, Table 1, increased from an initial value of 0.022 to 0.038 at 319-325°C, with 2,000 Vdc applied, after 91 hours in 50 psig CO_2 plus 138 hours in 2 psig CO_2, 2 hours before failure. The oxidative effect of the CO_2 may have been a cause for this dissipation factor increase, which was a reason for testing in N_2.

In pressurized N_2, the dissipation factor of the stack decreased from 0.02 to 0.0175, while that of the single winding did not change during aging.

RC

According to the lowest measured RC of 3 s, in CO_2, Table 1, and indeed the RC of 13 s at ~345°C in N_2, the dc resistivity of the mica paper dielectric at the elevated temperatures would contribute insignificantly to the power losses (dissipation factor).

CONCLUSIONS

Mica paper-Al foil-pressurized N_2 offers a stable high temperature capacitor system to operate at 300°C to just below 325°C with a dielectric energy density of 0.024 J/cm^3 (voltage stress = 40 V/µm, $\varepsilon_r = 3.4$). This was established by the reported life tests and dielectric measurements on test capacitor windings and a full-size, 2.4 µF, 7- layer stack capacitor. Commercialization of this capacitor will require optimization of preconditioning and the pressure, and reduction of voltage stress for operation at ~350°C.

Packaging of this capacitor calls for a flexible metal can to maintain the required pressure over the operating temperature range, and for low inductance ceramic bushing.

This capacitor can be economically produced in large volume with currently available capacitor manufacturing processes and materials.

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OPSEC REVIEW CERTIFICATION

(AR 530-1, Operations Security)

I am aware that there is foreign intelligence interest in open source publications. I have sufficient technical expertise in the subject matter of this paper to make a determination that the net benefit of this public release outweighs any potential damage.

Reviewer: Terence Burke ____ GS-14 ____ Electrical Engineer ____
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